

# **Ocean Surface Wave Optical Roughness - Innovative Measurement and Modeling**

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## **LONG-TERM GOALS**

We are part of a multi-institutional research team\* funded by the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program are to (1) examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) construct a radiance-based SBL model; (3) validate the model with field observations; and (4) investigate the feasibility of inverting the model to yield SBL conditions. The goals of our team are to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.

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## **OBJECTIVES**

Nonlinear interfacial roughness elements - sharp crested waves, breaking waves as well as the foam, subsurface bubbles and spray they produce, contribute substantially to the distortion of the optical transmission through the air-sea interface. These common surface roughness features occur on a wide range of length scales, from the dominant sea state down to capillary waves. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale microscale breakers that do not entrain air. There is substantial complexity in the local wind-driven sea surface roughness microstructure. Traditional descriptors of sea surface roughness are scale-integrated

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statistical properties, such as significant wave height, mean squared slope (eg. Cox and Munk, 1954) and breaking probability (e.g. Holthuijsen and Herbers, 1986). Subsequently, spectral characterisations of wave height, slope and curvature have been measured, providing a scale resolution into Fourier modes for these geometrical sea roughness parameters. More recently, measurements of whitecap crest length spectral density (eg. Phillips et al, 2001, Gemmrich, 2005) and microscale breaker crest length spectral density (eg. Jessup and Phadnis, 2005) have been reported.

Our effort seeks to provide a more comprehensive description of the physical and optical roughness of the sea surface. We will achieve this by implementing a comprehensive sea surface roughness observational ‘module’ within the RADYO field program to provide optimal coverage of the fundamental optical distortion processes associated with the air-sea interface. Within our innovative complementary data gathering, analysis and modeling effort, we will pursue both spectral and phase-resolved perspectives. These will contribute directly towards refining the representation of surface wave distortion in present air-sea interfacial optical transmission models.

## APPROACH

We will build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team (listed above) measuring and characterizing the surface roughness. The group plans to contribute the following components to the primary sea surface roughness data gathering effort in RaDyO:

- *polarization camera measurements* of the sea surface slope topography, down to capillary wave scales, of an approximately 1m x 1m patch of the sea surface (see Figure 1), captured at video rates. [Schultz]
- *co-located and synchronous orthogonal 75 Hz linear scanning laser altimeter* data to provide spatio-temporal properties of the wave height field (resolved to O(0.5m) wavelengths) [Banner, Morison]
- *high resolution video imagery* to record whitecap data, from two cameras, close range and broad field [Gemmrich]
- *fast response, infrared imagery* to quantify properties of the microscale breakers, and surface layer kinematics and vorticity [Zappa]
- *sonic anemometer* to characterize the near-surface wind speed and wind stress [Zappa]

Our envisaged data analysis effort will include: detailed analyses of the slope field topography; laser altimeter wave height and large scale wave slope data; statistical distributions of whitecap crest length density in different scale bands of propagation speed and similarly for the microscale breakers, as functions of the wind speed/stress and the underlying dominant sea state. Our contributions to the modeling effort will focus on using the data to refine the sea surface roughness transfer function. This comprises the representation of nonlinearity and breaking surface wave effects including bubbles, passive foam, active whitecap cover and spray, as well as microscale breakers.

## WORK COMPLETED

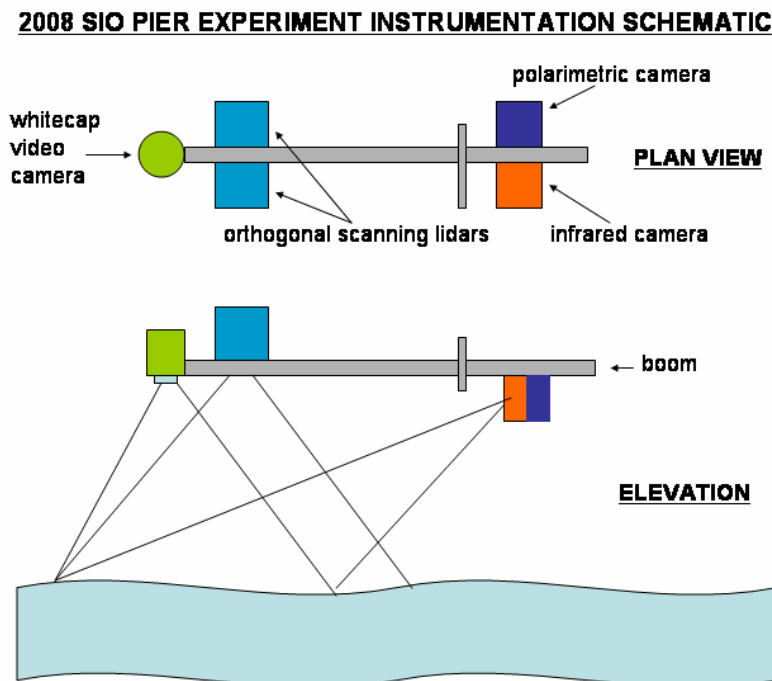
Our effort in FY07 has been primarily in the detailed planning of the suite of sea surface roughness measurements that we will undertake during the Scripps Institution of Oceanography (SIO) Pier Experiment scheduled for January 6-28, 2008. During FY07 we refined our choices of the instrumentation needed to make the measurements described in the preceding section, and continued work on the analysis techniques for characterizing the various roughness features. We participated in the FY07 RaDyO scientific planning meetings, which were held in Montreal in October 2006 and at SIO in June 2007.

We carried out data processing and validation of our scanning lidar data gathered at the USACE Duck pier field site at Duck, N. Carolina. Two of these instruments, operating in quadrature, will be deployed in the RaDyO field experiments to monitor the large scale wave geometry (height and slope components). We also progressed with our development of a robust ‘individual wave’ decomposition capability so that local physical roughness elements can be detected and characterized along with their space-time phasing, thereby overcoming the classical Fourier spectrum issue of bound versus free wave contributions in assessing true physical sea surface roughness.

## RESULTS

(i) Instrumentation proposed for the SIO pier experiment, January 6-28, 2008.

Figure 1 below shows schematically the instrumentation to be deployed in this field testing phase.



**Figure 1. Schematic of instrumentation packages to be deployed from the northern swinging boom at the end of the Scripps pier. The end of the instrumentation boom will be about 9m from the edge of the pier and about 10m above the mean water level. The approximate field of view of the various instruments is shown. Another wide angle whitecap video camera is mounted well above the pier.**

Banner/Morison plan to deploy two orthogonal line scanning lidars, synchronized for zero crosstalk. These will be positioned on the boom so that their intersection point is within the common footprint of the polarimetric (Schultz), infrared (Zappa) and visible (Gemmrich) imagery cameras to measure small-scale surface roughness features and breaking waves.

Zappa will deploy his infrared/visible camera system (with blackbody target, a blackbody controller, a laser altimeter). He will also deploy his environmental monitoring system (sonic anemometer, a Licor water vapor sensor, a Vaisala RH/T/P probe, a motion package, a pyranometer, and a pyrgeometer).

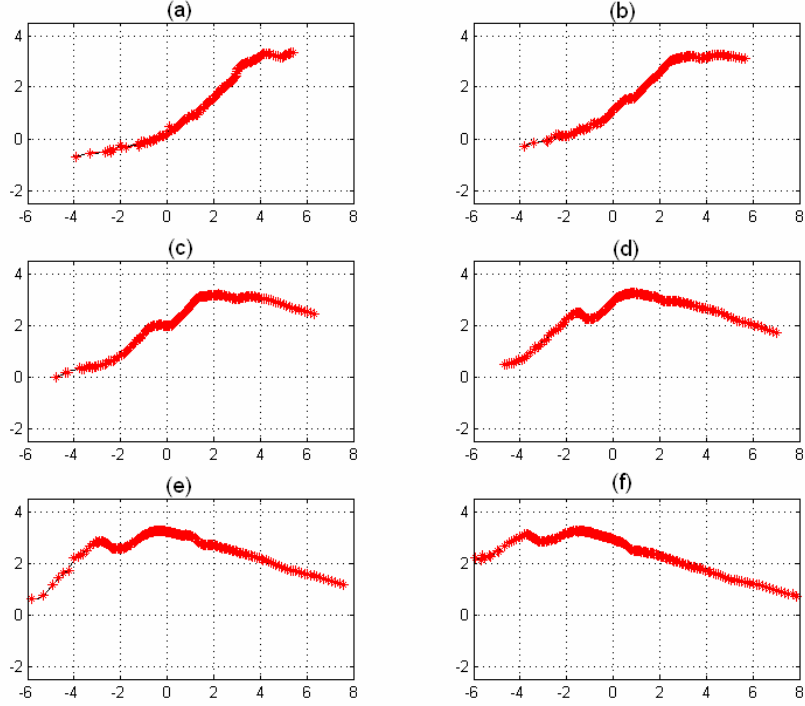
Gemmrich will deploy 2 video visible imagery cameras. One camera will be mounted on the main boom next to our other instrumentation packages. The second camera will be mounted higher up to provide a wider perspective on larger scale breaking events.

Schultz/Corrada-Emmanuel will deploy an instrument package located on the boom that includes a polarimetric camera imaging the very small-scale waves, an autofocus controller for this camera, a laser rangefinder for the autofocus mechanism, a polarimetric camera looking up at the sky and a motion package.

The individual data acquisition systems will be synchronized to GPS accuracy so that the various data sets can be interrelated.

#### (ii) Duck pier scanning lidar breaking wave profiles

Our scanning lidar system was field-tested at the Duck pier site over a wide range of conditions where the wind speed  $U_{10}$  ranged from light and variable, up to 16 m/s. Figure 2 shows typical scanning lidar data over breaking waves under strong wind forcing conditions.



**Figure 2.** Panels (a) through (f) show the temporal evolution of the surface elevation profile measured by our scanning lidar of a breaking wave shoaling in 7m water depth at the Duck pier site. The observed wave geometry shows a very steep leading face, with a maximum steepness approaching  $45^\circ$ . Note the persistent feature developing on the forward face. The  $x$  and  $z$  axes show distances in meters. The time interval between the successive images is 0.176 seconds.

The lidar was deployed from a boom at a height of 9m above the mean sea level, where the water depth was about 7m. The lidar sensing spot on the sea surface had a diameter of  $\sim 0.2$ m, it made an altimetric height determination every  $0.5^\circ$  and the temporal scan rate was in excess of 50 Hz. With its viewing window of  $\pm 45^\circ$  to the vertical, the maximum horizontal data extent was  $\pm 9$ m from nadir.

We deployed this instrument for several days. As anticipated, the horizontal extent of the lidar return increased as the wind strengthened, because of the greater number of scatterers that provide the specular return facets for the lidar to make its time-of-flight measurement. Our experience confirmed that this method will provide useful data on the height and local directional slope of the dominant waves. This information characterizes the background environment experienced by the short wind waves (the sea surface microstructure roughness). This information will also allow accurate phasing of the polarimetric camera imagery of the sea surface microstructure with respect to the underlying dominant wind waves.

### (iii) surface roughness data analysis

As a component of our data analysis effort, we continued our effort to develop new phase-resolved descriptions of sea surface roughness. In addition to state-of-the-art Fourier (e.g. Elfouhaily et al., 2003) and wavelet techniques, we are investigating various ‘riding wave’ analyses (RWA). This

approach envisages an ‘individual wave’ decomposition capability so that local physical roughness elements can be detected and characterized along with their space-time phasing, thereby overcoming the classical Fourier spectrum issue of bound versus free wave contributions in assessing true physical sea surface roughness.

## **IMPACT/APPLICATIONS**

This effort will provide a far more detailed characterization of the wind driven air-sea interface, including wave breaking (whitecaps and microscale breaking). This is needed to provide more complete parameterizations of these processes, which will improve the accuracy of ocean optical radiative transfer models and trans-interfacial image reconstruction techniques.

## **RELATED PROJECTS**

The present project is related generically to our current ONR sea surface wave project in the CBLAST Hurricane DRI entitled: ‘Wave breaking influence in a coupled model of the atmosphere-ocean wave boundary layers under very high wind conditions’. While the wind speed regimes in RaDyO and CBLAST Hurricanes are very different, common elements in these two projects include the need to better understand and parameterize the breaking process and how it occurs at the different wave scales.

Our CBLAST effort has resulted in a capability for forecasting wave breaking of the dominant waves. These forecasts validate well at moderate wind speeds of around 12 m/s. Validation of hurricane breaking waves awaits the data processing by other CBLAST PIs. Our effort has also highlighted the need to better understand breaking at the shorter scales, where the breaker frequency statistics appear to fall off towards shorter scales. However, balancing wind input to short waves with breaker dissipation rate, present modeling suggests that short wave breaking statistics should increase towards shorter scales. We will revisit this issue with the new insights provided by our RaDyO datasets.

## **REFERENCES**

- Cox, C.S. and Munk, W.H., 1954: Measurements of the roughness of the sea surface from photographs of the sun glitter. *J. Opt. Soc. Am.* 44, 838-850.
- Elfouhaily, T., S. Guignard, H. Branger, D.R. Thompson, D. Vandemark and B. Chapron, 2003: Time-frequency applications with the Stokes-Woodward technique, *IEEE Geoscience and Remote Sensing Letters*, 41—11, 2670-2673.
- Gemmrich, J, 2005: ‘On the occurrence of wave breaking’, 14th 'Aha Huliko'a Hawaiian Winter Workshop, January 2005, Proceedings, Eds. P. Muller et al., 123-130.
- Holthuijsen, L.H., and T.H.C. Herbers, 1986: Statistics of breaking waves observed as whitecaps in the open sea, *Journal of Physical Oceanography*, 16, 290-297.
- Jessup, A.T. & Phadnis, K.R. 2005 Measurement of the geometric and kinematic properties of microscale breaking waves from infrared imagery using a PIV algorithm. *Meas. Sci. Technol.* 16, 1961-1969.

Phillips, O.M., Posner, F.L. and Hanson, J.P., 2001: High resolution radar measurements of the speed distribution of breaking events in wind-generated ocean waves: surface impulse and wave energy dissipation rates. *J. Phys. Oceanogr.*, 31, 450–460.

## **PUBLICATIONS**

### ***M.L. Banner***

Donelan, M.A., A.V. Babanin, I.R. Young, M.L. Banner, and C. McCormick, 2004: Wave follower measurements of the wind input spectral function. Part I. Measurements and calibrations. *J. Atmos. Ocean Tech.*, 22, 7, 799-813. [published, refereed]

Young, I.R., M.L. Banner M.A., Donelan, A.V. Babanin, W.K. Melville, F. Veron and C. McCormick, 2004: An integrated system for the study of the wind wave source term balance in finite depth water. *J. Atmos. Ocean Tech.*, 22, 7, 814-828. [published, refereed]

Song, J. and M.L. Banner, 2004: On the influence of mean water depth and a subsurface sand bar on the onset and strength of wave breaking. *J. Phys. Oceanogr.*, 34, 950-960. [published, refereed]

E. J. Walsh, M.L. Banner, J.H. Churnside, J.A. Shaw, D.C. Vandermarke, C.W. Wright, J.B. Jensen and S. Lee, 2005: Visual demonstration of three-scale surface roughness under light wind conditions. *IEEE J. Geoscience and Remote Sensing*, 43, 1751-1762. [published, refereed]

Donelan, M.A., A.V. Babanin, I.R. Young and M.L. Banner, 2006: Wave follower field measurements of the wind input spectral function. Part II. Parameterization of the wind input. *J. Phys. Oceanogr.*, 36, 1672-1688. [published, refereed]

M.L. Banner and R.P. Morison, 2006: On modeling spectral dissipation due to wave breaking for ocean wind waves. 9th Int'l Workshop on Wave Hindcasting and Forecasting, Victoria, B.C., Canada, Sept. 24-29, 2006 [published]

M.L. Banner & W.L. Peirson, 2007: Wave breaking onset and strength for two-dimensional deep water waves. *J. Fluid Mech.*, 585, 93-115. [published, refereed]

A.V. Babanin, M.L. Banner, I.R. Young and Donelan, M.A., 2007: Wave follower field measurements of the wind input spectral function. Part III. Breaking wave enhancement. *J. Phys. Oceanogr.* [in press, refereed]

E. J. Walsh, M. L. Banner, C. W. Wright, D. C. Vandemark, B. Chapron, J. Jensen, S. Lee, 2007: The Southern Ocean Waves Experiment, Part III. Sea surface slope statistics and near nadir remote *sensing*. *J. Phys. Oceanogr.* [in press, refereed]

### ***R.P. Morison***

Tan, K.A., R.P. Morison, and L.M. Leslie, (2005): A comparison of high-order explicit and non-oscillatory finite difference advection schemes for climate and weather. *Meteor. Atmos. Phys.*, 89, 251-267. [published, refereed]



M.L. Banner and R.P. Morison, 2006: On modeling spectral dissipation due to wave breaking for ocean wind waves. 9th Int'l Workshop on Wave Hindcasting and Forecasting, Victoria, B.C., Canada, Sept. 24-29, 2006 [published]